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Optics Communications 280 (2007) 431–434
Optics Communications
www.elsevier.com/locate/optcom

Performance analysis of a FTTH link utilizing asymmetric data transmission

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Received 29 May 2007; received in revised form 4 August 2007; accepted 9 August 2007

Abstract

A WDM–PON recycling incoming light to transmit upstream data has been analyzed. Effect of Rayleigh scattering, uneven energy distribution and noise accumulation are evaluated to achieve 80 km bidirectional communication with <64× asymmetry factor.

1. Introduction

There have been many research and development efforts placed on next generation optical access networks to provide low cost and broadband connectivity to multimedia and data communication users [1]. WDM–PON is one of the most favorable approaches to provide large bandwidth [2–14]. However, the light source requirement at the user end is a big challenge in terms of initial deployment and maintenance. Since this requirement will increase the cost per user and require large backup inventory, alternative approaches have been sought. Recently there have been several efforts placed to eliminate the light sources at the user end by using carrier re-modulation technique [2–14]. These approaches recycle the incoming light source by using reflective semiconductor optical amplifiers (RSOA). However, most of these proposed approaches either require time division multiplexing of the source located in the central office for upstream and downstream communication [4–9] or complicated modulation and filtering schemes to generate clean signal for upstream communication [2–5,8–11]. Recently, direct modulation of incoming data has been proposed and implemented in a bidirectional link [12,13]. This approach is rather attractive because it does not require any pre-processing of the incoming signal. However, effect of Rayleigh scattering, which is a main bottleneck in bidirectional communication [15,16], effect of uneven energy distribution and noise accumulation have never been discussed in detail in these reports.

In this paper we analyze a dense WDM–PON structure which recycles the incoming downstream data stream without any pre-processing and takes advantage of asymmetric nature of current data traffic [12,13]. The simulation results show that the true PRBS nature of incoming data will allow error free bidirectional communications with ∼10–100× asymmetry (10 Gb/s downstream and 156 Mb/s–1 Gb/s upload) in each channel. The system performance is mainly impaired by the noise accumulation, Rayleigh backscattering and uneven energy distribution of upstream data bits. In this work we focus on the power requirement, randomness of the data and asymmetry factor which can give error free maximum reach in bidirectional fiber link. By carefully adjusting the power levels in both directions, error free transmission up to 80 km can be achieved at 64× asymmetry. Increasing the upstream data rates to over 1 Gb/s will result in 11 dB reduction in electrical Q values. However, despite the limitation of uneven energy distribution, 10 dB electrical Q values can be achieved over a >50 km communication link carrying 10 Gb/s downstream traffic and 625 Mb/s upstream traffic. We show that performance is significantly higher when randomness reduces to $2^7 - 1$ PRBS [3,13,14] from $2^{18} - 1$ PRBS.

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doi:10.1016/j.optcom.2007.08.048

2. Modulation scheme and performance analysis

Fig. 1a illustrates the modulation concept used in these simulations. Downstream data is generated by modulating a DFB laser at 10 Gb/s. The upstream data is directly encoded on top of the received signal, Fig. 1b. Here the envelope contains the information about the upstream data and 10 Gb/s modulation underneath the envelope needs to be discarded at the receiver. This was achieved by using a low pass electrical filter at the receiver end at the central office. Fig. 2 illustrates the schematic diagram of network architecture used in our model. The central office generates 10 Gb/s broadcast signal and processes the upstream data transmitted by the end user terminal. In this work we assume central office transmits 10 Gb/s $2^{18}-1$ PRBS data with on–off ratio of 10 dB. Similarly, the end user terminal receives the broadcasted 10 Gb/s signal and splits into two. First part is sent to a receiver and the second half is recycled to transmit upstream data by using reflective semiconductor amplifiers (RSOA). After amplification in an EDFA with 6 dB noise figure, the transmitted signal passes through a ~10 dB lumped loss element to address loses generated by different components such as splitters and wavelength multiplexers in practice. The gain of the EDFA is adjusted accordingly to tune the power per channel launched into the fiber between 0.1 and 10 mW. The fiber is standard SMF fiber with 0.25 dB/km fiber loss and dispersion value of 20 ps^2/km. At the user end, part of the selected wavelength will be sent to a RSOA to generate upstream data. The loss between the end of the transmission fiber and the RSOA in a double pass is set to be 12 dB to take losses induced by various components into the account. We assume up to 20 mW saturated output with 6 dB noise figure and ~30 dB small signal gain in the semiconductor amplifier is achievable [11,17]. We use 6 dB noise figure for strong input powers. For weak input powers the NF is raises up to 20 dB [11,17]. We use NRZ data format for transmission for both directions. We solve nonlinear Schrodinger equation to calculate the signal profile after propagation. The Rayleigh scattering is assumed to be −27 dB/km [18].

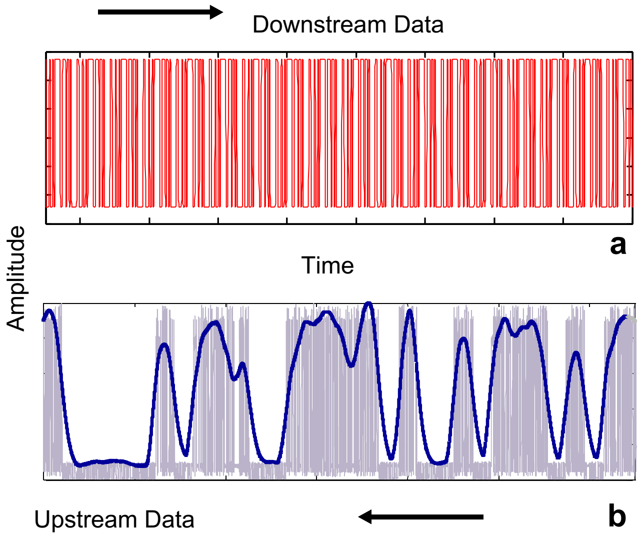

Fig. 1. Modulation scheme for (a) downstream data and (b) upstream data.

The system performance is evaluated based on the estimated Q value of the received signal at the central office. Q calculation is a widely used technique to directly measure the eye opening of the received signal: $Q=\frac{\mu_1-\mu_0}{\sigma_0+\sigma_1}$, where $\mu_{1,0}$ and $\sigma_{1,0}$ illustrates the average values and standard deviations of level "1" and level "0", respectively, [19]. Fig. 3, illustrates an exemplary eye diagram of received upstream data at the central office. Since each upstream bit will contain different numbers of "0"s and "1"s underneath it, they will suffer from uneven energy distribution. This will be reflected as a large variance at "0" due to the limited extinction ratio of optical modulators and "1" levels due to energy variation on the eye diagram. However, this effect will be more pronounced for level "1" and hence Q values are mostly determined by the variance of level "1". Similar to upstream data, the downstream data will suffer from Rayleigh scattering. However, noise accumulation and uneven energy distribution will be insignificant for downstream data. Here, we ignore the system performance of the downstream traffic and only focus on the upstream traffic.

First we analyze the effect of Rayleigh scattering on system performance. Fig. 4a illustrates the system performance for different downstream power for 2 mW upstream power. As estimated results indicate, error free communication is achievable up to 60 km if the Rayleigh scattering is low for low downstream power. As the downstream power increases to 10 mW, system performance decreases due to increased Rayleigh scattering. At these power levels noises generated by the EDFA and the RSOA will have minimal effect in simulation powers even RSOA NF is increased to 10 dB. At very low power values (0.1 mW), the system performance is, as expected, noise limited. However, the maximum reach can be increased if the power levels at both ends are optimized, Fig. 4b. The results indicate that the increasing of the upstream power will overcome the Rayleigh limitation and facilitate error free communication over 80 km at 20 mW reflected power level. Practically, the saturated output power and small signal gain of RSOAs will limit the maximum reach.

In addition to Rayleigh scattering, uneven energy distribution of received upstream data will reduce the system performance. Ideally, a CW light source is desired to encode upstream data for error free operation. If the random downstream bit is recycled for upstream data, different upstream bits will have different energies due to the fact that each bit will contain different pattern underneath it. Probability of having long consecutive zeros in downstream data will raise the standard deviation of level "1" and level "0" which, in turn, will diminish the Q values. As the upstream bitrates increase, the probability of having upstream bit level "1" encoded on top of consecutive "0"

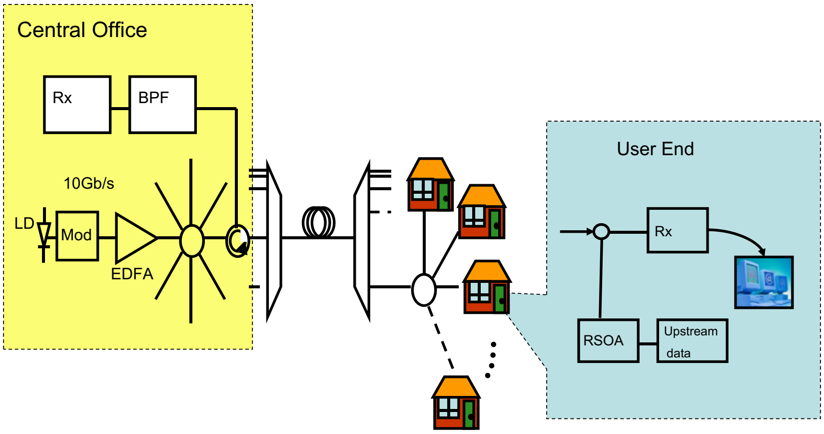

Fig. 2. Network configuration under study. WDM– PON is constructed to recycle download bit stream and facilitate bidirectional operation.

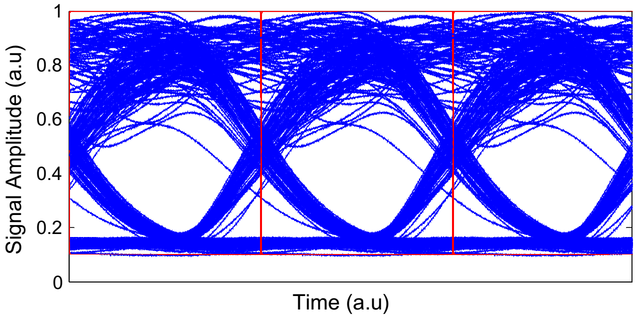

Fig. 3. Eye diagram of 156 Mb/s upstream data received at the central office.

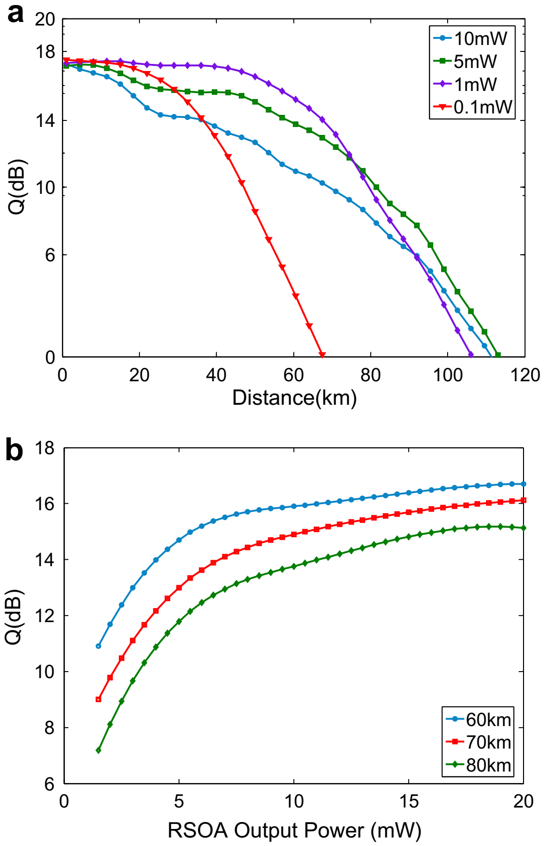

Fig. 4. (a). Estimated Q values versus distance for four different power levels of downstream data measured after the EDFA in the central office; (b) estimated Q value versus RSOA output power for three different propagation distances from central office to the user end.

bits coming from downstream data increases. As a result, the Q values will decrease for lower asymmetry factors. As illustrated in Fig. 5, the Q values decrease more than 11 dB if the asymmetry factor reduces to 10 to transmit 1 Gb/s upstream data due to uneven energy distribution. However, >60 km bidirectional communication is feasible at 312 Mb/s with ~14 dB Q values.

The uneven energy distribution problem is also related to randomness of the downstream data. To asses the effect of random variations in a bit stream we compare two different PRBS data streams. The first bit stream is generated based on $2^7 - 1$ PRBS to limit consecutive zeros to 7. The second is based on $2^{18} - 1$ PRBS which allows longer consecutive zero patterns in downstream data. Fig. 6 illustrates the effect of data pattern on the system performance assessed by $2^7 - 1$ and $2^{18} - 1$ PRBS. In this part, the Rayleigh scattering is turned off to highlight the effect of asymmetry factor. As expected, for $2^7 - 1$ PRBS data stream, the variations in pulse energies are lower and hence the Q values are >4 dB higher compared to $2^{18} - 1$ PRBS at high asymmetry factors (64×). However, as the upstream bitrates increase, the probability of having upstream bit level “1” encoded on top of consecutive zeros coming from downstream data increases. As a result, even $2^7 - 1$ PRBS data stream will suffer from uneven energy distribution at low asymmetry factors but it might be tolerable. Previous studies have confirmed these claims by experimental work [3,6,8,12–14]. Because of mentioned problems, symmetric data transmission at more realistic data streams ($2^{18} - 1$ PRBS) has never been demonstrated by direct modulation of the incoming signal. These results indicate that the proposed network architecture will support large asymmetries and will fail for high bit rate upstream data. Since, current passive optical networks provide lower than 100 Mb/s data

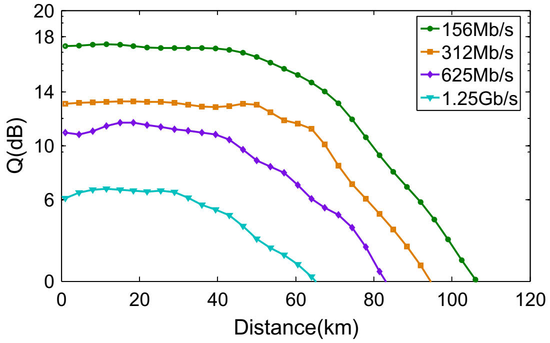

Fig. 5. Q value versus distance with four different upstream bitrates.

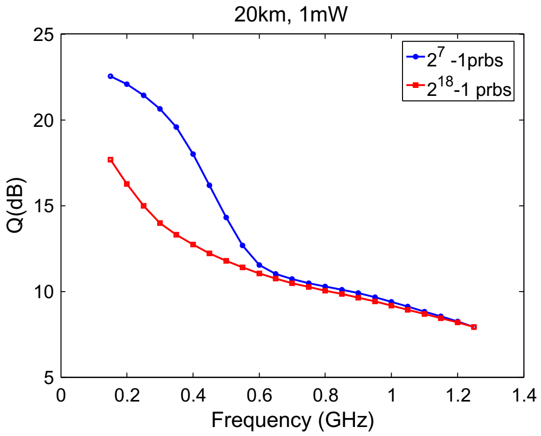

Fig. 6. Effect of data pattern on system.

rate per user, this configuration can be an alternative scheme for a low cost next generation PON. Alternatively, using special encoding schemes such as 8B/10B may alleviate the effect of consecutive “0”s and allow high speed upstream communication at the expense of redundancy.

3. Conclusion

In summary, we analyze the performance of a WDM–PON structure which utilizes RSOAs to encode upstream data without any pre-processing and take advantage of asymmetric nature of access networks. We show that Rayleigh scattering and uneven energy distribution are two main contributors to Q value degradation at moderate power levels. Rayleigh scattering can be mitigated by power optimization. Uneven energy distribution, on the other hand, is related to asymmetry factor and randomness of the downstream data. By carefully adjusting the power levels in both directions, error free transmission up to 80 km can be achieved at 64× asymmetry factor. Reducing the asymmetry factor will result in lower Q values and shorter transmission distances.

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